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Adaptive Optics for Large Telescopes

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Adaptive Optics for Large Telescopes
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Summary
The use of adaptive optics was originally conceived by astronomers seeking to correct the blurring of images made with large telescopes due to the effects of atmospheric turbulence. The basic idea is to use a device, a wave front corrector, to adjust the phase of light passing through an optical system, based on some measurement of the spatial variation of the phase transverse to the light propagation direction, using a wave front sensor. Although the original concept was intended for application to astronomical imaging, the technique can be more generally applied. For instance, adaptive optics systems have been used for several decades to correct for aberrations in high-power laser systems. At Lawrence Livermore National Laboratory (LLNL), the world's largest laser system, the National Ignition Facility, uses adaptive optics to correct for aberrations in each of the 192 beams, all of which must be precisely focused on a millimeter scale target in order to perform nuclear physics experiments.

Over the past two decades, LLNL has also been a pioneer in the development of astronomical adaptive optics and laser guide star systems, having developed the first successfully combined adaptive optics and sodium-layer laser guide star systems for the 3-meter Shane Telescope at Lick Observatory on Mt. Hamilton near San Jose, California, and subsequently delivering similar laser and wave front correction systems for the 10-meter Keck II Telescope on Mauna Kea, Hawaii. This work has been a premier example of the application of technology, originally developed at LLNL for the U.S. Dept. of Energy, National Nuclear Security Administration, to basic science research in collaboration with the University of California.

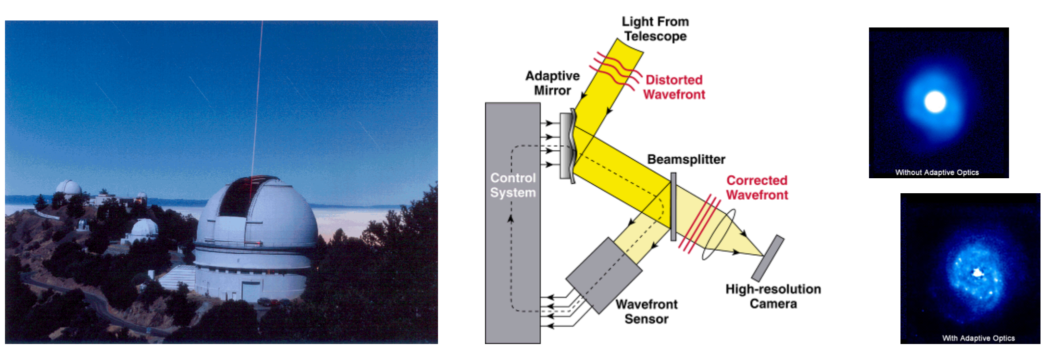

Figure 1 – Beam for sodium-layer laser guide star propagating from the dome of 3-meter Shane Telescope at Lick Observatory on Mt. Hamilton near San Jose, California (left panel); schematic of astronomical adaptive optics system (center panel); images of a spiral galaxy with (bottom right panel) and without (top right panel) adaptive optics correction (photo credit: Canada-France-Hawaii Telescope).

The performance of adaptive optics for astronomical imaging, laser beam control, or other applications, is dependent on the characteristics of the wave front corrector technology. Many adaptive optics systems have been based on thin, deformable glass mirrors with discrete, electro-active ceramic actuators. Another deformable mirror technology uses a bimorph design with thin layers of electro-active ceramic materials combined with thin glass or other optical substrates. A third deformable mirror design, pioneered at the University of Arizona for use as adaptive secondary mirrors on large telescopes, is based on electromagnetic actuation, accomplished by passing a current through a wire coil surrounding a permanent magnet.

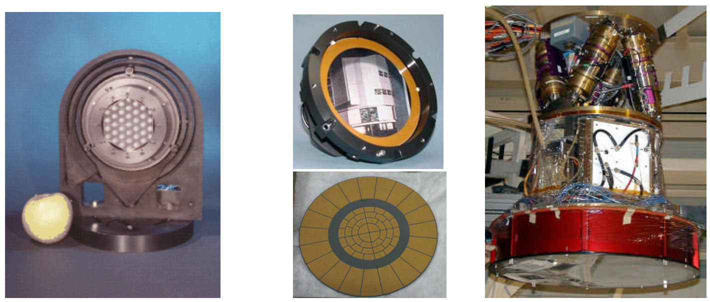

Figure 2 – Three types of deformable mirrors based on (1) discrete, electro-active ceramic actuators (left panel), (2) thin layers of electro-active ceramic materials (center panels; photo credit: Canada-France-Hawaii Telescope), (3) macroscopic electromagnetic actuators (right panel; photo credit: University of Arizona).

A different deformable mirror design that has become increasing popular over the last decade is based on electrostatic actuation of micro-electro-mechanical systems (MEMS) technology. The development of MEMS deformable mirrors has been a major objective of the National Science Foundation Center for Adaptive Optics (CfAO). Founded in 1999, and headquartered at the University of California, Santa Cruz, the CfAO supports research and education in adaptive optics. Research within the CfAO, involving a dozen universities and two dozen research labs, observatories and companies, is focused in three thematic areas in astronomy and vision science. For astronomy, CfAO researchers are investigating adaptive optics techniques and technologies for both extremely large telescopes (e.g., 30-meters) and ultra-high-contrast imaging needed to image extra-solar planets. In vision science, CfAO researchers are exploring the use of adaptive optics for correction of ocular aberrations in the eye to enhance retinal imaging and enable new psychophysical studies.

MEMS deformable mirrors have played an increasing important role in CfAO adaptive optics research. The relatively small size and potentially large number of actuators for relatively low cost has made MEMS deformable mirrors attractive for both vision science and astronomy. In vision science at least eight operational systems have been constructed by CfAO researchers using MEMS devices, including two systems that received R&D 100 awards from R&D Magazine in 2003 and 2007 as one of the 100 most technologically significant innovations of those years. In astronomy a MEMS device with 4000 actuators is the basis of the design for the Gemini Planet Imager, a facility instrument being developed for the 8-meter Gemini Telescopes in order to image hundreds of extra-solar planets. MEMS devices are also being considered by CfAO researchers in the design of future instruments for the Thirty Meter Telescope.

Most of the adaptive optics systems developed or designed by CfAO researchers using MEMS deformable mirrors have been based on devices produced by a spin-off company from Boston University, Boston Micromachines Corp. (BMC). The development of the BMC MEMS devices was significantly advanced by a DARPA program in Coherent Communications Imaging and Targeting. This program, led by LLNL in the early 2000's, successfully demonstrated the application of MEMS spatial light modulator technology and interferometric wave front sensing to the problem of correcting aberrations in a laser beam propagating over long distances through the atmosphere. For this program, BMC developed MEMS devices with 1000 actuators and established the feasibility of the type of device required for imaging extra-solar planets using ground-based telescopes.

Although, the small format of MEMS devices provides the opportunity for new uses of adaptive optics, one challenge for these devices has been the capability to provide a large dynamic range for the control of aberrations. However, recent work at Sandia National Laboratory has demonstrated MEMS deformable mirrors with a range of motion up to 25 microns. An alternative approach for achieving large dynamic range in a small form factor, developed in a French national laboratory and commercialized by the company, Imagine Optics, uses miniature electromagnetic actuators, similar in concept to the actuators used for large deformable telescope secondary mirrors. Devices of this type offer a range of motion up to 50 microns or more in a relatively small form factor, although the actuator density is more than an order of magnitude larger than for a typical MEMS device.

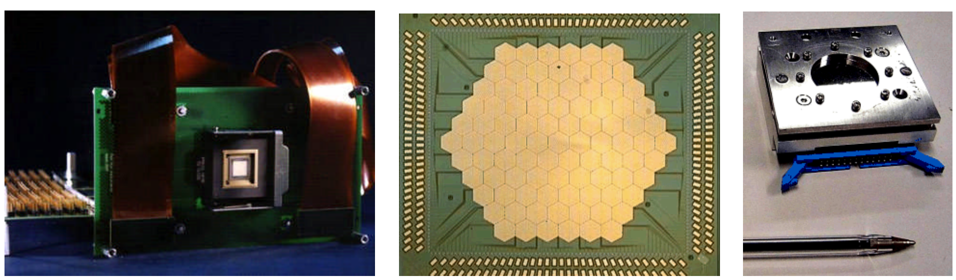

Figure 3 – Three types of small deformable mirrors based on (1) electrostatic deformation of micro-electro-mechanical systems (MEMS) actuators supporting a continuous mirror membrane (left panel), (2) electrostatic deformation of MEMS actuators controlling discrete mirror segments (center panels; photo credit: Sandia National Laboratory), (3) mesoscopic electromagnetic actuators (right panel; photo credit: Imagine Optics).

Adaptive optics systems developed to compensate for the effects of atmospheric turbulence on large, ground-based telescopes have generally used relatively small mirrors placed in a re-imaged, de-magnified pupil of the telescope. The reason for this is that it is difficult to move large mirrors at speeds necessary to compensate for the effects of atmospheric turbulence (~1 kHz). The largest mirror with which compensation for atmospheric turbulence has been demonstrated is the 1.6-meter Gregorian secondary mirror for the Large Binocular Telescope. However, the basic concepts of adaptive optics are now generally applied to the larger optics of big telescopes in order to correct for aberrations caused primarily by gravitational and thermal effects, similar to the use of adaptive optics techniques to correct for aberrations due to thermal effects in high-power laser systems. These uses of adaptive optics concepts are often distinguished using the term “active optics” to refer to aberration correction at slower speeds than required for compensation of the effects of atmospheric turbulence. Nevertheless, the basic ideas remain similar, requiring some ability to adjust the shape of the primary and other large optics, along with some ability to measure the spatial variation of the phase of light propagating through the system.

One methodology for active control of a large primary mirror is exemplified by the Keck Telescopes, which use a segmented primary mirror design. The primary mirror segments can be made relatively thin, reducing the overall weight of the primary mirror, and therefore also reducing the overall cost of the telescope. This methodology is being extended to the design of the Thirty Meter Telescope, which is planned to use ~500 segments to construct a primary mirror with a diameter of 30 meters. To maintain good image quality, both the Keck Telescopes and the Thirty Meter Telescope must control the positions of the mirror segments to an accuracy of less than the wavelength of light. This is accomplished, using an active control system that monitors and adjusts the positions of the mirrors ~once per second. While the active optics control frequency for maintaining the shape of the large primary mirror is much lower than adaptive optics frequency of ~1000 Hz required to compensate for atmospheric turbulence, the principles are similar.

The use of both active and adaptive optics is now nearly ubiquitous for large, ground-based telescopes. The Keck Telescopes and the Thirty Meter Telescope are examples of telescopes that actively control the large telescope mirrors to compensate for gravitational and thermal effects and also employ adaptive optics to compensate for atmospheric turbulence. On the Keck Telescopes, adaptive optics systems are utilized in combination with multiple instruments, including infra-red cameras, spectrometers, and an interferometer that combines the light from both Keck Telescopes to provide measurements with extremely high spatial resolution. For the Thirty Meter Telescope, an infra-red spectrograph utilizing adaptive optics is planned as one of the first generation instruments, and four additional adaptive optics concepts are being studied for potential implementation to support the second generation of instrumentation.

For telescopes located in space, adaptive optics to compensate for atmospheric turbulence is unnecessary since the telescope is outside of the atmosphere. However, active optics techniques can be important for maintaining the shape of telescope optics in space, which are subject to bending stresses due primarily to differential heating on orbit and misalignments during initial deployment. The James Webb Space Telescope is designed to compensate for these effects using the same methodology as the Keck Telescopes, by utilizing a primary mirror made up of thin segments. In the case of the James Webb Space Telescope, these segments are made of beryllium rather than glass to reduce their weight and the telescope is designed to unfold once on orbit after launch in order to fit into the launch vehicle. This on-orbit deployment scheme requires further capability to position the segments actively with high precision over a large dynamic range, which necessitates the use of sophisticated active optics techniques.

In addition to space-based telescopes, certain types of ground-based telescopes, such as wide-field survey telescopes, may also derive little benefit from adaptive optics, but may rely on sophisticated active optics to maintain image quality. For instance, the Large Synoptic Survey Telescope is designed to utilize a novel, three-mirror design to image a field of view of 9.6 square degrees. This telescope will have an 8.4-meter primary mirror, a 3.4-meter secondary mirror and a 5-meter tertiary mirror. The optimized optical design produces excellent image quality over the entire field from ultra-violet to near infra-red wavelengths. In order to maintain image quality during operation, the deformations and rigid body motions of the three large mirrors must be actively controlled to minimize optical aberrations, arising primarily from gravitational and thermal effects. This will be accomplished utilizing a tomographic methodology for measuring the telescope aberrations using a set of curvature wavefront sensors located in the four corners of the telescope focal plane. This tomagraphic technique will also be applicable for wide-field, space-based telescopes.

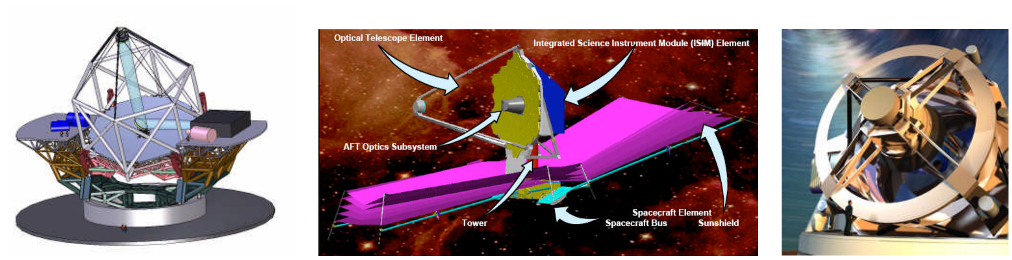

Figure 4 – Three types of large telescopes designed to use active optics (1) the Thirty Meter Telescope, with a primary mirror consisting of ~500 segments with active position and figure control (left panel; photo credit: TMT Project), (2) the James Webb Space Telescope, with a primary mirror consisting of 36 segments with active position and focus control (center panels; photo credit: NASA), (3) the Large Synoptic Survey Telescope with three large, continuous mirrors with active position and figure control (right panel; photo credit: LSST Corporation).

Future space telescopes could also benefit from further advances in lightweight optics technology in order to reduce the overall system weight, thereby enabling larger systems to be launched with a given launch vehicle. However, in general, advances in lightweight optics must also be coupled with advances in the ability to actively control the shape of these optics. One approach for producing advanced lightweight optics, being developed by the company, Xinetics, uses a thin, multi-layer metallic foil attached to a deformable silicon carbide substrate with integrated electro-active ceramic actuators. The process of fabricating the “nanolaminate” foil with the required optical properties has been developed at LLNL using sputter deposition techniques similar to those used to produce coatings for x-ray optics. Another approach for producing advanced lightweight optics, which has been studied extensively at the Air force Research Laboratory, involves the use of thin polymer membranes which can be deformed through a variety of techniques, including electrostatic actuations, similar in concept to MEMS deformable mirrors.

Based on ongoing progress, a notional roadmap for future large space telescopes can be constructed. For the lightweight optics, the next 5 years will likely see the development of meter-scale components with an areal density of ~10 kg/m^2, and within the next 20 years, components may be developed with sizes from 1 to 100 meters and with areal densities of ~1 kg/m^2. In terms of the deformation capabilities of lightweight optics, the next 5 years will likely see the development of components that may be deformed on lateral spatial scales from 1 to 0.1 meters, and with an accuracy of between 100 to 10 nanometers, and within the next 20 years, components may be developed that may be deformed on lateral spatial scales from 0.1 to 0.01 meters, and with an accuracy of between 10 and 0.1 nanometers. Further elements of a roadmap would include the development of system concepts using lightweight, deformable optics, the development of deployment concepts using lightweight, deformable optics, improvements in rapid manufacturing of large, lightweight optics, advances in wave front sensing and control methods, and demonstration of technologies on orbit.

In order to realize the potential envisioned for future, large space telescopes, numerous difficult technical issues will need to be addressed. These include: (1) the development of new active materials and structures for large, lightweight, high-precision optics, for which the optical surface is required to be lightweight, smooth, deployable, and deterministically and repeatably controllable at the nm level over lateral spatial scales from millimeters to meters in the orbital environment, (2) the development of optical systems with the capability for distributing the control signals to the active materials, (3) the development of integrated schemes for wave front sensing and control on orbit.

An extraordinary opportunity for overcoming these technical challenges exists through the paradigm of collaborative, multidisciplinary, multi-institutional programs supporting an integrated set of basic and applied research projects in the context of comprehensive systems engineering. This approach, which has been adopted, for instance by the National Science Foundation’s Science and Technology Centers, has succeeded in overcoming similar technical challenges, such as the development of MEMS adaptive optics systems capable of enabling large, ground-based telescopes to image planets around nearby stars.

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